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# The Accuracy of the Navy-Standard Surf Model-Derived Modified Surf Index and its Sensitivity to Nearshore Bathymetric Profile Errors

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The Naval Research Laboratory's Remote Sensing Applications Branch has evaluated the sensitivity of the Navy-Standard Surf Model to nearshore bathymetric profiles, primarily focusing on the modified surf index (MSI) accuracy. The Navy-Standard Surf Model was first introduced in 1988 and is now used extensively throughout the Fleet as part of the Geophysical Fleet Meteorological Program Library and the Tactical Environmental Support System. The model is the primary software for objective forecasting of surf conditions and its accuracy is highly dependent upon the accuracy of the model inputs. The two most important inputs are the nearshore depth profile or bathymetry and the offshore wave conditions. This report describes the performance of the model relative to bathymetric profile errors. Model sensitivity to these errors is important for estimating model accuracy in denied areas where bathymetric data is less complete.

The Navy-Standard Surf Model was tested against field measurement data obtained from the DELILAH experiment held at the Duck, NC, Field Research Facility in 1990. Offshore directional wave spectra, wind, longshore current, wave height, depth profile, tide, and surf zone width measurements provided a rigorous data set for evaluating model performance and sensitivity. This study focused on field measurements obtained during the week of 6–12 Oct 1990. Daily nearshore depth profiles were used to evaluate model accuracy relative to profile age and slope estimation error. The latter was calculated by synthetically altering the valid profiles to contain percentage slope errors. Rudimentary bottom composition-based profiles were also utilized. A total of 373 surf model runs were made using valid wind, tide, and wave inputs for the various bathymetric profiles. The statistical analysis consists of tabulations, graphical plots, and accuracy measures. The MSI root-mean-square (RMS) fractional error

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relative to DELILAH measurements was calculated for each day. The error calculations were further broken down to identify MSI fractional RMS errors due to bathymetric age, slope estimation errors, and model geophysical error.

The overall error of the Navy-Standard Surf Model MSI was found to be approximately 22% when using the best wind, wave, tide, and bathymetric information available. The most significant inaccuracy in the model physics is in longshore current estimation. Although present research continues to focus on this issue, small improvements have been attained to date. Surf zone research emphasis should continue on longshore current modeling.

The age of the bathymetric profile was found to be very important. Out-of-date bathymetric profiles generated MSI fractional RMS errors of 19–44%, depending on the profile age. The bathymetric profile slope estimation error was also found to be important. MSI fractional errors between 0–25% were generated depending on the magnitude of the slope estimation error. Estimating a profile slope steeper than it actually is results in MSI values that are too high. Estimating slope errors shallower than they actually are generally generates MSI values that are too low, although this relationship is more complex and influenced by offshore bars.

MSI forecasts containing less than 10% error were found to require bathymetric profiles less than 1 d old and having less than 10% slope error. The sign of the bathymetric slope error is significant. Techniques used to estimate bathymetric slope should be careful not to overestimate the actual slope at all, but also not to underestimate the slope by more than 10–20%. Utilization of rudimentary bottom composition-based depth profiles resulted in MSI errors of 28%. These results seriously question the utility of historical bathymetric data base information and simple bottom composition-based depth profiles for near-real-time surf condition forecasts. Such profiles cannot generate accurate MSI forecasts. This report has also demonstrated that model improvements are necessary and that accurate bathymetric inputs to the model are critical.

# CONTENTS

## EXECUTIVE SUMMARY

The Naval Research Laboratory's Remote Sensing Applications Branch has evaluated the sensitivity of the Navy-Standard Surf Model to nearshore bathymetric profiles, primarily focusing on the modified surf index (MSI) accuracy. The Navy-Standard Surf Model was first introduced in 1988 and is now used extensively throughout the Fleet as part of the Geophysical Fleet Meteorological Program Library and the Tactical Environmental Support System. The model is the primary software for objective forecasting of surf conditions and its accuracy is highly dependent upon the accuracy of the model inputs. The two most important inputs are the nearshore depth profile or bathymetry and the offshore wave conditions. This report describes the performance of the model relative to bathymetric profile errors. Model sensitivity to these errors is important for estimating model accuracy in denied areas where bathymetric data is less complete.

The Navy-Standard Surf Model was tested against field measurement data obtained from the DELILAH experiment held at the Duck, NC, Field Research Facility in 1990. Offshore directional wave spectra, wind, longshore current, wave height, depth profile, tide, and surf zone width measurements provided a rigorous data set for evaluating model performance and sensitivity. This study focused on field measurements obtained during the week of 6–12 Oct 1990. Daily nearshore depth profiles were used to evaluate model accuracy relative to profile age and slope estimation error. The latter was calculated by synthetically altering the valid profiles to contain percentage slope errors. Rudimentary bottom composition-based profiles were also utilized. A total of 373 surf model runs were made using valid wind, tide, and wave inputs for the various bathymetric profiles. The statistical analysis consists of tabulations, graphical plots, and accuracy measures. The MSI root-mean-square (RMS) fractional error relative to DELILAH measurements was calculated for each day. The error calculations were further broken down to identify MSI fractional RMS errors due to bathymetric age, slope estimation errors, and model geophysical error.

The overall error of the Navy-Standard Surf Model MSI was found to be approximately 22% when using the best wind, wave, tide, and bathymetric information available. The most significant inaccuracy in the model physics is in longshore current estimation. Although present research continues to focus on this issue, small improvements have been attained to date. Surf zone research emphasis should continue on longshore current modeling.

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# THE ACCURACY OF THE NAVY-STANDARD SURF MODEL-DERIVED MODIFIED SURF INDEX AND ITS SENSITIVITY TO NEARSHORE BATHYMETRIC PROFILE ERRORS

## 1.0 INTRODUCTION

An essential element in the success of amphibious operations is a series of accurate surf forecasts covering the period of initial planning through completion of logistics over the shore. The surf zone can be a very dangerous place and the importance of surf conditions to amphibious and other naval and military operations are explicitly stated in several recent publications by the Joint Chiefs of Staff (1989, 1991, 1992, 1993). In view of the tremendous number of people and equipment that must confront the surf zone during an operation, it is critical that the on-scene commander be aware of its natural hazards. If conditions are forecast to be lower than encountered, lives and equipment could be put in jeopardy; forecasting conditions too high could limit a commander's options.

For naval and military operations, the surf is described by six different, but related properties (Commander, Naval Surface Force, Pacific and Commander Naval Surface Force, Atlantic 1987): height of the highest one-third of breaking waves, the time period between successive breaking waves, the angle between breaking waves and the beach, the type of breaking waves, and longshore (littoral or lateral) current.

The Navy-Standard Surf Model is the primary software for objective surf forecasting. Model inputs are offshore wave height, period, and direction; wind direction and speed; and the nearshore bathymetric depth profile. Model outputs are the six properties describing the surf and a single, dimensionless number called the modified surf index (MSI) that provides a relative estimate of overall surf conditions. The accuracy of surf model-derived MSI depends on the accuracy of the model and the model inputs. The two most important inputs are the offshore wave conditions and the nearshore depth profile.

This report documents the accuracy of model-derived MSI and the effect of nearshore depth profile errors on MSI estimation. The study was accomplished by running the surf model with, and comparing its outputs to, data acquired from 6–13 Oct 1990 at Duck, NC, during the intensively surf zone instrumented Duck Experiment on Low-Frequency and Incident-Band Longshore and Across-Shore Hydrodynamics (DELILAH [Field Research Facility 1991]).

This report briefly describes the Navy-Standard Surf Model and the modifications made to it for this study. Field measurements used as model inputs and/or validation are also described. The accuracy of model-derived MSI is documented along with its sensitivity to depth profile errors. It is shown that model-derived MSI is accurate to approximately 22% and that nearshore depth profiles 1 d old can cause MSI errors as high as 42%. Accurate bathymetric profiles less than 1 d old and possessing less than 10% slope error are required for MSI estimates with less than 10%

error. Use of rudimentary bottom-composition-based depth profiles resulted in MSI errors of 28%. These results seriously question the utility of historical bathymetric data base information and simple bottom-composition-based depth profiles for near-real-time surf condition forecasts. This report closes with a discussion regarding model and data input improvements necessary for accurate MSI calculation and application.

## 2.0 SURF MODEL

The Navy-Standard Surf Model software has been used extensively throughout the Fleet since it was introduced to the Navy in 1988. The Navy-Standard Surf Model is now a part of the suite of software used in the Geophysical Fleet Meteorological Program Library and the Tactical Environmental Support System. The software was developed because previous surf forecasting techniques were based on methods dating back to the 1950s using mainly manual techniques that do not adequately consider local shallow-water effects. The theory and numerical methods for the model are described in Earle (1989), its operating instructions are given in Earle (1988), and improvements to the model are described in Earle (1991).

The model is parametric and one dimensional. Deep-water wave energy is refracted and shoaled to a user-selected starting depth outside of the surf zone. At the model starting depth, the refracted and shoaled directional wave energy distribution is compressed based on Higgins et al. (1981) to three representative physical values: the direction of the vertically averaged wave momentum flux, the root-mean-square (RMS) wave height $h_{rms}$, and the dominant wave frequency ($1/T_p$) with $T_p$ representing dominant wave period. This compression of the wave spectrum is based on Higgins et al. (1981). The model incrementally calculates $h_{rms}$ from the starting depth to the still-water level along a transect normal to the beach using the local depth and the wave height found at each previous increment. As waves move through the surf zone, the average rate of energy dissipation due to wave breaking and frictional dissipation balances the gradient of shoreward energy flux. Energy is extracted using the energy dissipation of a propagating bore modeled after a Rayleigh distribution of wave heights. Longshore current calculations at each increment are based on radiation stress longshore current theory.

The width of the surf zone is considered to be the farthest offshore point at which either more than 33% of the waves are breaking or the point at which there is maximum wave energy dissipation. The significant breaker height, $h_{sig} = \sqrt{2} \cdot h_{rms}$, and the longshore current $v$ are considered to be highest in the surf zone. The percentage of each breaker type—spilling, plunging, or surging—is obtained from a widely accepted parameterization of wave period, wave height, and bottom slope. Dominant wave period is conserved within the model. Breaker angle is acquired from the starting depth vertically averaged wave momentum flux direction. MSI is calculated using the criteria given in the *Joint Surf Manual* (Commander, Naval Surface Force, Pacific and Commander, Naval Surface Force, Atlantic 1987) that uses the surf zone properties to provide essentially one relative and dimensionless estimate of surf conditions.

The model software used in this study was developed from SPE_SURF (Mettlach et al. 1996), to which three modifications and one correction were made. First, the model was modified to specifically read DELILAH sensor directional wave spectra files. The standard model does not have an option for directly utilizing measured wave spectra. The standard model internally generates a directional wave spectrum from input sea and swell parameters. Input sea parameters of height, period, and direction are used to produce a modified Pierson-Moskowitz spectrum. Input swell parameters of height, period, and direction are also used to produce a spectrum that is

narrow-banded in frequency and direction. If both sea and swell parameters are fed into the model together, the two internally generated spectra are superimposed to form one directional wave spectrum. SPE_SURF was developed to take advantage of the information available from the Navy WAve model. The version used in this study is an enhancement of SPE_SURF that allows direct input of the highly resolved DELILAH spectra measurements. The primary advantage of using spectra directly for a validation study is that broad assumptions about the shape of the directional wave spectrum are abandoned.

The second modification to the model involves refraction and shoaling of the DELILAH spectra. The model was expanded to include straight coast refraction and shoaling of input wave energy from intermediate depths. The straight coast refraction and shoaling calculations contained in SPE_SURF are based on the assumption that input wave energy is deep-water wave energy only (Earle 1989, *op cit,* pp. 11–12). The modifications that were made properly refract and shoal wave energy from the 26-ft (8-m) DELILAH directional array to 12 ft (3.7 m), the depth at which surf zone calculations were selected to begin. This modification reduces uncertainty about the initial wave conditions at the model starting point. Third, the software was modified for use on a Pentium PC using Microsoft Fortran 77 version 5.10. The model was tested extensively and no compiler dependencies were found. Finally, a minor error in the original surf model calculation of energy dissipation was corrected to properly reflect the bore dissipation equation given in Earle (1989, *op cit,* p. 15) and Thornton and Guza (1983, *op cit,* Eq. 26).

## 3.0 EXPERIMENT

### 3.1 Modified Surf Index and its Use in This Study

The definition and application of MSI is given in the *Joint Surf Manual* (Commander, Naval Surface Force, Pacific and Commander, Naval Surface Force, Atlantic 1987, *op cit,* ch. 11, p. 11-1): "*The Modified Surf Index is a single dimensionless number which provides a relative measure of the conditions likely to be encountered in the surf zone. For the reported or forecast conditions, MSI provides a guide for judging the feasibility of landing operations for each type of landing craft* [except the Landing Craft Air Cushion (LCAC) hover craft and other newer vehicles]. . . *When applied to a known or forecast surf condition, the modified surf index calculation provides the commander with an objective method of arriving at a safe and reasonable decision with respect to committing landing craft and amphibious vehicles. Limiting conditions for training operations shall be set by the commander concerned. These limits shall not exceed conditions acceptable for routine operations as calculated by the objective method* [of the modified surf index]." Since the MSI contains the relative importance of the various surf zone properties, i.e., breaker height, longshore current, breaker angle, etc., it provides a benchmark for evaluating the surf model in terms of its reliability for operational applications.

The surf model was run 373 times inputting DELILAH data and various depth profiles. All wind, tide, and wave inputs were obtained from DELILAH data. The resulting 373 MSI values are analyzed and compared.

### 3.2 Field Measurements

DELILAH was held in 1990 at the U.S. Army Corps of Engineers Waterways Experiment Station, Coastal Engineering Research Center's Field Research Facility (FRF) located in Duck, NC.

The experiment deployed 87 instruments from the shoreline out to the 3-m (10-ft) depth contour and collected a vast amount of data useful to many coastal research efforts. The intent of DELILAH was: "*To measure the wave and wind forced three-dimensional nearshore dynamics with specific emphasis on infragravity wave, shear waves, mean circulation, set-up, runup, and wave transformation. To also monitor the bathymetric response to these processes.*" (FRF 1991). The data collected during DELILAH make it possible to rigorously evaluate the performance of the surf model and to study its sensitivity to input error. Note that a wealth of information about, and data from, DELILAH and the FRF is available at *http://frf.wes.army.mil.*

Table 1 contains the input data, except the depth profiles and wave spectra information, used for the surf model runs. Other information used to validate the model-derived MSI values, as well as the offshore wave conditions, are also given in this table. The following subsections give details of the DELILAH measurements used in this study.

### *3.2.1 Offshore Directional Wave Spectra*

Directional wave spectra used as input to the surf model were acquired at a nine-element linear array of bottom-mounted pressure gauges located on the 8-m (26-ft) contour about 900 m (0.5 nmi)

Table 1 — Model Inputs, Offshore Wave Parameters, and Validation Data

| DD | HH (EST) | TIDE (ft) | WSPD (kt) | WDIR (deg) | $h_{sig}$ (ft) | $\theta_p$ (deg) | $T_p$ (s) | $SZ$ (ft) | $h_{sig\_b}$ (ft) | $v$ (kt) |
|---|---|---|---|---|---|---|---|---|---|---|
| 06 | 16 | −0.9 | 13.2 | −49.7 | 1.7 | −30 | 10.7 | 195 | 1.77 | 1.0 |
| 07 | 07 | 2.2 | 10.1 | −112.1 | 2.0 | −28 | 10.7 | (180) | 2.27 | 0.6 |
| 08 | 16 | −1.6 | 12.2 | −64.6 | 2.3 | −26 | 10.7 | 260 | 2.70 | 1.6 |
| 09 | 13 | 0.5 | 13.9 | −64.7 | 3.4 | −26 | 10.7 | 285 | 3.55 | 1.9 |
| 10 | 13 | 1.5 | 18.2 | −75.4 | 3.9 | −30 | 10.7 | (300) | 3.98 | 1.7 |
| 11 | 10 | 1.3 | 19.9 | −81.7 | 5.3 | −38 | 8.9 | (300) | 3.27 | 2.4 |
| 12 | 10 | 1.2 | 12.0 | 13.6 | 4.0 | −20 | 8.2 | 340 | 4.10 | 1.5 |

DD is day, Oct 1990. HH is hour and 00 min
Acquisition time of data = HH to HH + 2 h 16 min
Tide from 8-m array pressure sensor
Wind measurements at 19.4 m (63.7 ft)
WSPD is wind speed
WDIR is wind direction
Directions are positive counter-clockwise (CCW) from shore normal (= 070° N)
Wave measurements at 8-m array 1/2 mi offshore
$h_{sig}$ is significant wave height
$T_p$ is dominant wave period at the 8-m array
$\theta_p$ is the dominant wave direction at 8-m array
$SZ$ is surf zone width from video (estimates without video are in parentheses)
$h_{sig\_b}$ is the highest measured mean significant wave height in the surf zone over acquisition time
$v$ is the highest measured mean longshore current in the surf zone over the acquisition period

offshore. Table 2 gives information on the data acquisition and processing of the directional wave spectra by FRF. The basic analysis algorithm is the iterative maximum likelihood estimator derived and described by Pawka (1983).

### *3.2.2 Wind Measurements*

Mean vector wind direction and mean wind speed were obtained from time series of wind direction and wind speed acquired concurrently with the directional array data from an anemometer 19.4 m (63.7 ft) above mean sea level on the beach.

### *3.2.3 Longshore Current in the Surf Zone*

Longshore current measurements were acquired from an array of nine current meters located along a transect normal to the shoreline and extending from near the water line to approximately 800 ft (245 m) offshore. Five-minute mean measurements covering the same time period as the directional array acquisition period were averaged and used to determine the maximum mean longshore current in the surf zone. These mean values are used in determining actual MSI over the acquisition time.

### *3.2.4 Wave Height in the Surf Zone*

Mean values of $h_{sig}$ were obtained from pressure sensors located in the same horizontal location as the current meters. Five-minute mean measurements covering the same time period as the directional array acquisition period were averaged and used to determine the maximum mean $h_{sig}$ in the surf zone. These mean values are used in determining actual MSI over the acquisition time.

### *3.2.5 Depth Profiles*

Two series of depth surveys were used to construct the nearshore depth profiles used with the model. The first series of surveys were the Deep Sled surveys that encompassed an area 1600 m

Table 2 — Directional Wave Spectrum Information

| | |
|---|---|
| Length of Time Series Processed | 8192 s |
| Data Sampling Frequency of Time Series | 4 Hz |
| Number of Data Points in a Data Segment | 4096 points |
| Number of Frequency Bands Averaged | 15 bands |
| Number of Half-Lapped Segments Analyzed | 10 segments |
| Degrees of Freedom of Final Spectral Estimates | 160 dof |
| Number of Output Frequency Bands | 29 bands |
| Width of an Output Frequency Band | 0.00977 Hz |
| Number of Output Direction Bins (Arcs) | 91 directional arcs |
| Width of an Output Direction Bin | 2 deg |
| Depth of Measuring Array | 25.8 ft (7.86 m) |

(5250 ft) alongshore from near 100 m (328 ft) shoreward of the beach to 1800 m (5900 ft) offshore. Figure 1 is a contour map of the composite Deep Sled survey from the series provided by the FRF. This figure shows that the contours from the 8-m directional array to the surf zone sensors are largely straight and parallel to the beach; however, there is a deep trough under the FRF pier.

Figure 1 positions and depths are in the FRF coordinate system. The origin of the FRF coordinate system is the intersection of a shore-parallel baseline with the southern boundary of FRF property. Positive directions are toward 340° N alongshore and toward 070° N cross-shore. Elevation data are referenced to the 1929 National Geodetic Vertical Datum. The location of all sensors and data positions are known in FRF coordinates.

The second series of depth surveys, covering an area approximately 600 m (1967 ft) alongshore and 375 m (1230 ft) offshore to near the 4-m (13-ft) contour are called the minigrid surveys. The minigrid surveys were made daily during the course of DELILAH; however, the survey of 13 Oct 1990 is incomplete because of high waves on that day. Figure 2 is a contour map of one minigrid survey

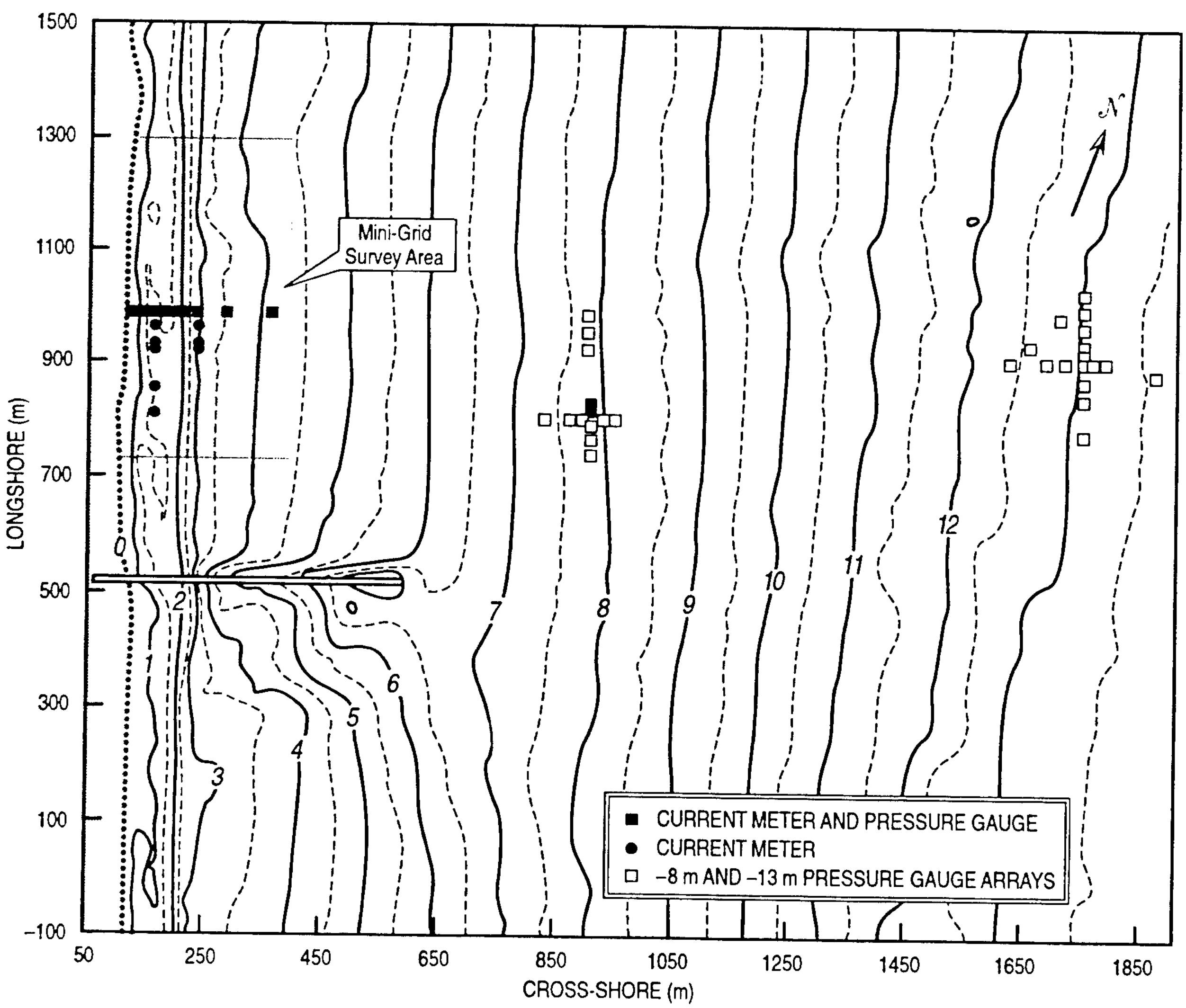


Fig. 1 — Deep sled survey contour map with the minigrid area outlined

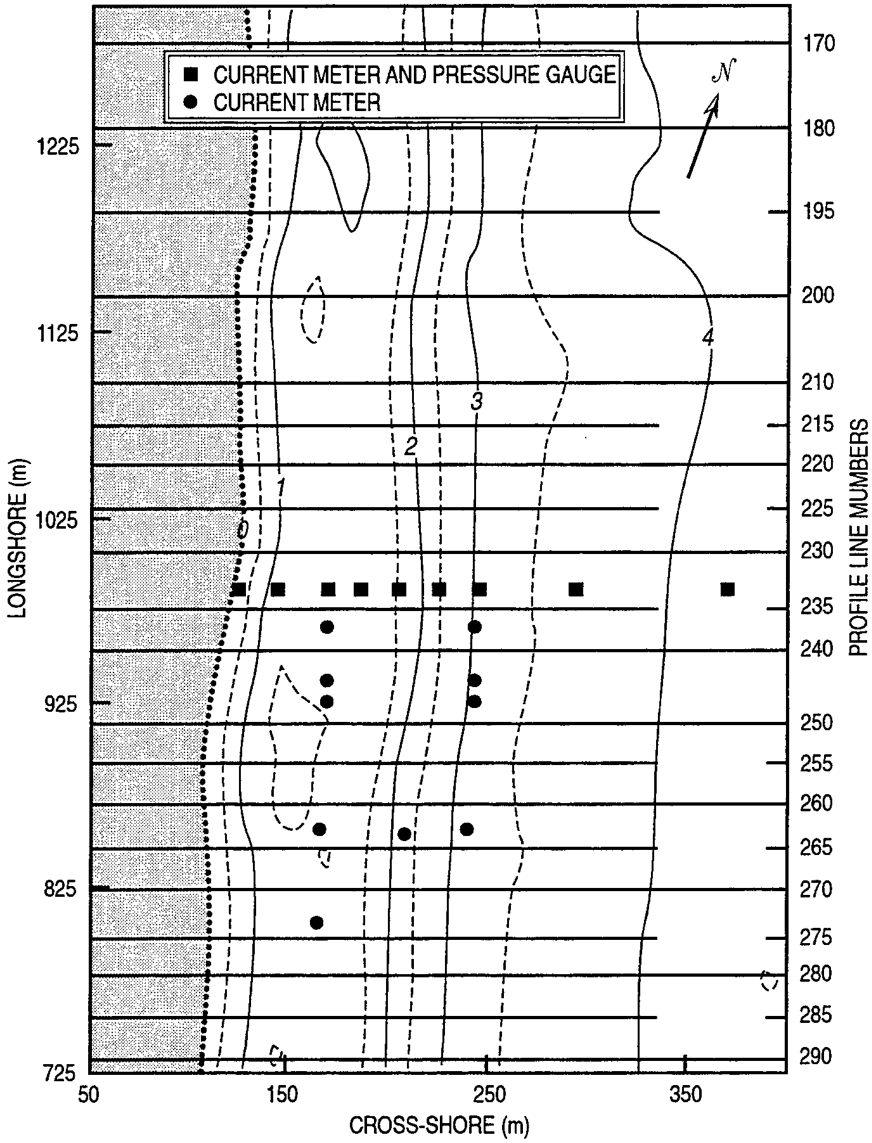


Fig. 2 — DELILAH minigrid profile lines

and includes the positions of the surf zone sensors. The sensors that provided surf zone significant wave height and longshore current in this study are located along a cross-shore transect at 985 m alongshore.

A single depth profile cross-shore of the 985-m line was constructed by taking all deep sled measurements within 25 m either side of the 985-m line. Seven nearshore depth profiles were constructed from the minigrid profiles of 6–12 Oct by taking measurements 10 m either side of the 978-m line (978 m was used because this was the closest survey line to the surf zone sensors). The single deep sled line was merged with each of the minigrid lines by replacing all deep sled measurements over the range of minigrid measurements with minigrid measurements.

Figure 3 is a plot of the seven depth profiles used in this study. This figure reveals dramatic changes in the nearshore bathymetry over the period, notably the erosion of the beach and the formation of a well-defined offshore bar. Not shown in this figure is the convergence of the profiles above the beach berm and below 12-ft depth.

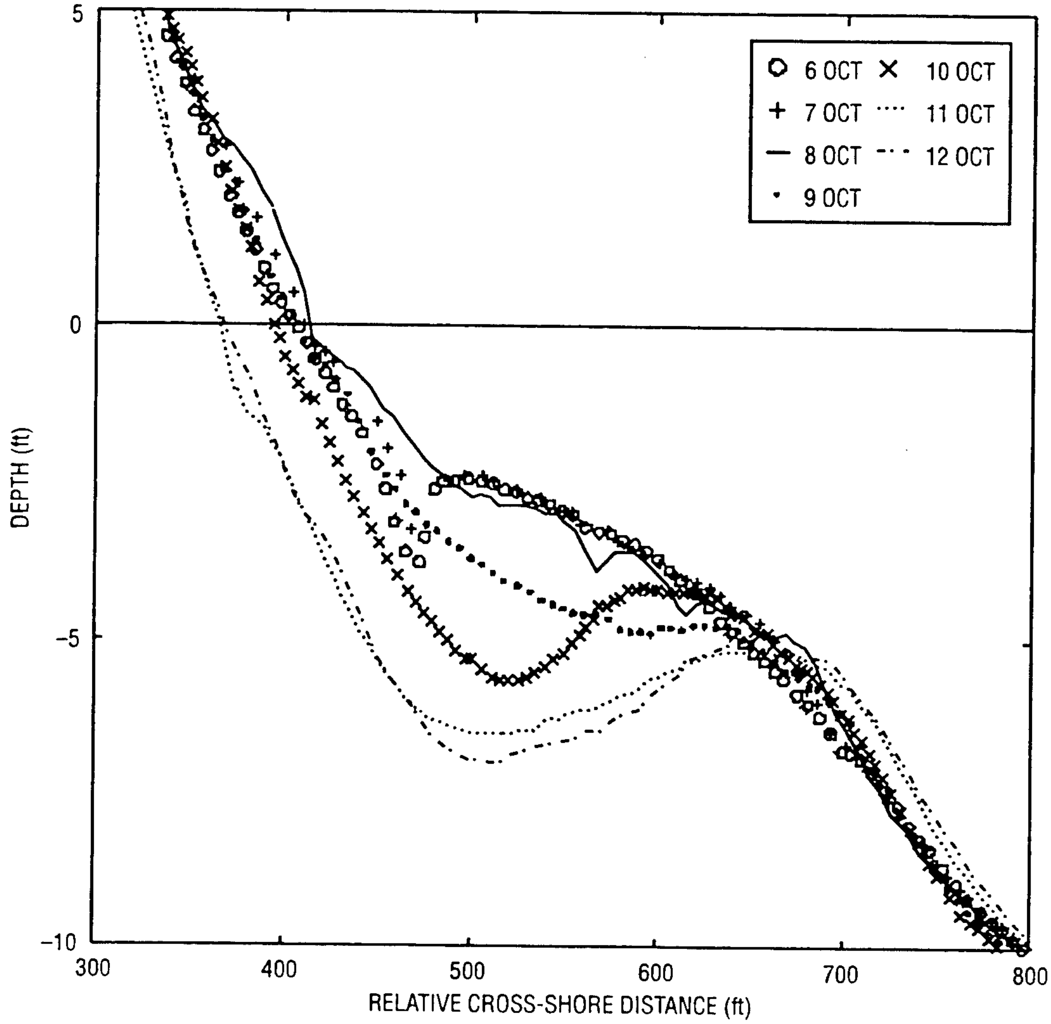


Fig. 3 — Depth profiles used for model runs. Horizontal axis is FRF cross-shore coordinate.

### *3.2.6 Tide Level*

Mean tide level over the acquisition time was obtained from a pressure gauge at the 8-m array. Tide level is used in the model to determine the still-water level. The same tide level was used for all runs for a given time.

### *3.2.7 Surf Zone Width*

Since MSI calculations are relative to the surf zone, the width of the surf zone must be determined for MSI validation. This is done using available DELILAH video imagery. Lippmann and Holman (1991) and Holman et al. (1993) have shown several applications of video image processing to the study of nearshore processes during DELILAH. Field Research Facility (1991, *op cit*, apps. B and C) gives detailed information on the location of cameras and ground coordinate points. Several 10-min averaged video image files in .jpg format and software for displaying and rectifying the images were provided by Prof. Rob Holman, Oregon State University.

Images acquired at, or sufficiently near, the same time as model run times (6, 8, 9, and 12 Oct) were analyzed by identifying the locations of maximum contrast between the offshore area of little or no breaking waves, represented by a dark area, and the offshore-most area of breaking waves, represented by an area of relatively high brightness. The distance between the still-water point determined from tide and depth profile data and the point of maximum contrast is assumed to be the width of the surf zone.

Figure 4 depicts one of the video images used. The upper image shows the camera view; the box drawn on the upper image is rectified to a horizontal plane in FRF coordinates and shown in the lower image. The 985-m line, the still-water point at 115 m, the point of maximum brightness at 194 m, and the point of maximum contrast at 218 m are denoted. The high brightness on either side of the still-water point shows surf run-up and set-down in the swash zone. When video imagery was not available, surf zone width was estimated by using the closest video images to the time and comparing the differences in wind and wave conditions between the times and assessing the model output.

### 3.3 Depth Profile Error Simulation

Twelve depth profiles with varying slope errors were made from each of the daily DELILAH depth profiles. Depth profiles with slope error $\gamma$ for time $t$ were made using the following formula:

$$d_{t,\gamma}(x) = (1 + \gamma)\, d_{t,0}(x)\,, \tag{1}$$

where $d$ is the depth, $t$ is the day, $x$ is the cross-shore coordinate, and $\gamma$ is the slope error, which was varied from –0.3 to 0.3 in increments of 0.05. The altered depth profiles are used to investigate the MSI error resulting from the percentage of slope error in the depth profile. This method provides a mechanism to quantify model errors due to bathymetric slope changes over time. In addition, various methods of estimating bathymetry profiles are actively being pursued and this method provides the means to quantify slope estimate error impact on model results.

### 3.4 Nearshore Depth Profile from Sediment Information

Three bottom-composition-based depth profiles were made based on the work of Dean (1977) who found that nearshore beach depth, $d_A(x)$ can be described by the functional relation

$$d_A(x) = A\, x^{2/3}, \tag{2}$$

where $A$ is an empirically derived constant functionally related to bottom sediment composition. Smith et al. (1993), citing Howd and Birkemeier (1987), state that the median grain size in the FRF nearshore varies from 0.7 mm on the steep foreshore (coarse sand, $A = 0.2$ [$m^{3/2}$]), to 0.2 mm on the bar (fine sand, $A = 0.09$ [$m^{3/2}$]) to 0.12 mm on the offshore (very fine sand, $A = 0.06$ [$m^{3/2}$]). These profiles are denoted $d_{foreshore}$, $d_{bar}$, and $d_{offshore}$.

Figure 5 contains plots of the bottom-composition-based depth profiles. The bottom-composition profiles were made from the program SEDIMENT, which is a utility program that is part of the Navy-Standard Surf Model package. This program is described in Earle (1988, 1989). It is noted that these profiles do not contain an offshore bar.

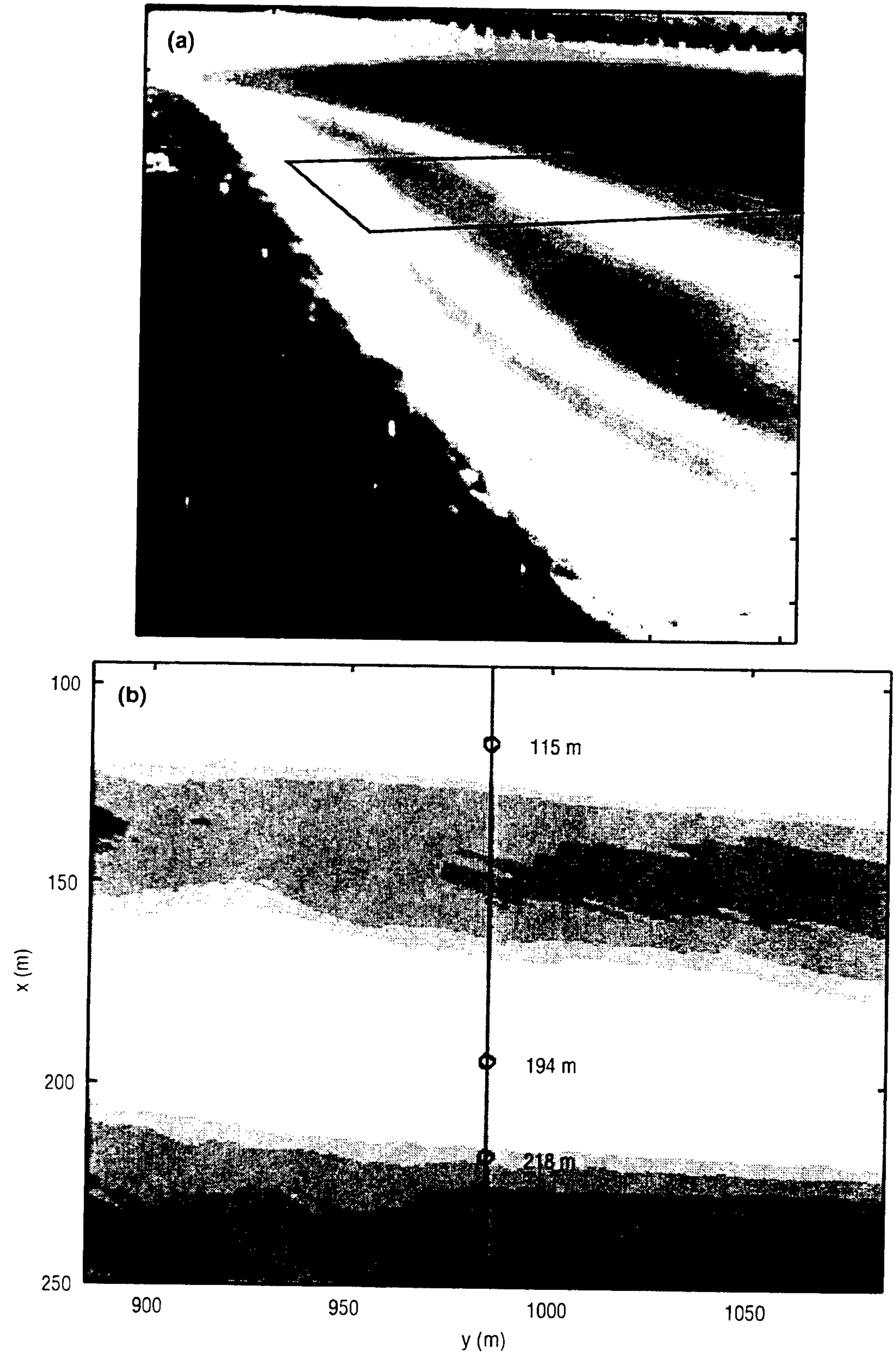


Fig. 4 — (a) 10-min averaged video image acquired 0856–0956 EST 12 Oct 1990. (b) Rectified image corresponding to the box in (a). Still-water point, maximum brightness, and maximum contrast seaward are noted along the 985-m transect.

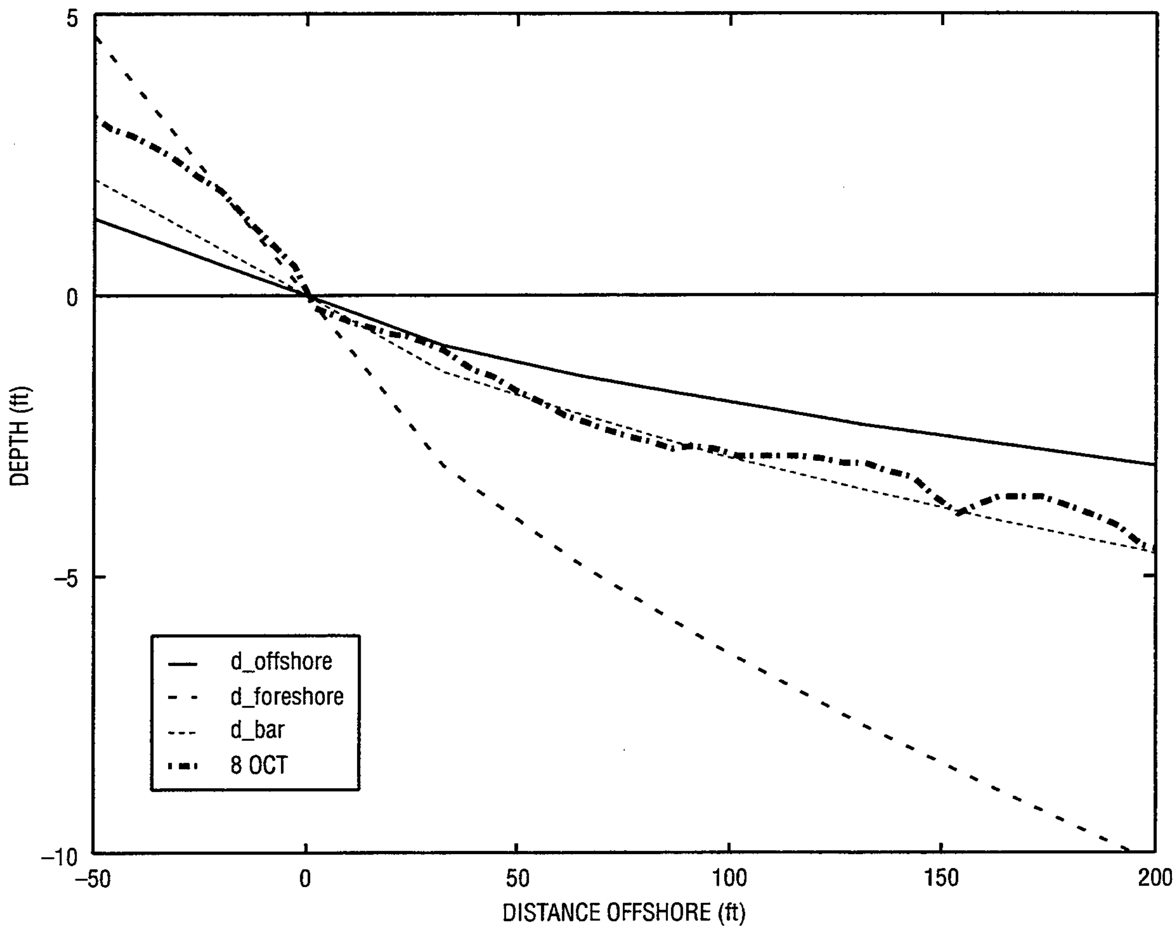


Fig. 5 — Depth profiles derived from program SEDIMENT and 8 Oct depth profile

### 3.5 Model Runs

A total of 373 surf model runs were made. Wind and tide data for each day are given in Table 1, as are the significant wave height, period, and direction from the directional wave spectra acquired at the offshore array. All model runs were made with a starting depth of 12 ft and a calculation interval of 4 ft. A measurement of 12 ft was used because it was close to, but not in, the surf zone. Once the model integration begins, energy is extracted due to dissipation processes. Bringing the starting depth as close to the surf zone as possible reduces the likelihood of spuriously extracting wave energy outside of the surf zone.

The 373 runs are grouped into four categories:

1. *Best Data Runs*. These runs were made using the best available DELILAH data for the time given. One run was made for each of the days, 6–12 Oct, in which all input data (i.e., wind, tide, and directional wave spectra) were DELILAH data that had been acquired concurrently. Profiles were those acquired on the same day as the other data (seven total runs).

2. *Bottom-Composition-Based Depth Profile Runs*. One run was made for each of the days, 6–12 Oct, using $d_{foreshore}$, $d_{bar}$, and $d_{offshore}$. All input data except the depth profiles were DELILAH data that had been acquired concurrently. These runs were made to test MSI accuracy based on assumed depth profiles (21 total).

3. *Old Depth Profile Runs.* A series of runs were made for each day, 7–12 Oct, in which all input data for the series were DELILAH data acquired concurrently, except that old depth profiles were used. For example, the 12 Oct series used depth profiles for 6–11 Oct, while all other input data were 12 Oct data. These runs were made to determine the influence of old or outdated profiles on MSI estimates (21 total).

4. *Depth Profile Error Runs.* A series of runs were made for each of the days, 7–12 Oct, in which all input data were DELILAH data acquired on the last day of the series. Depth profiles $d_{t,\gamma}$ from 6 Oct to the last day of the series and all non-zero $\gamma$ profiles were used. For example, the 12 Oct series included 84 runs in which $d_{t,\gamma}$ was varied such that $t$ = [6, 7, 8, 9, 10, 11, 12 Oct] and $\gamma$ = [−0.30, −0.25, −0.20, −0.15, −0.10, −0.05, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30], while all other input data were DELILAH data from 12 Oct. These runs were made to quantify depth profile slope error effects (324 total).

The 373 runs provide sufficient information to evaluate the accuracy of model-derived MSI, the accuracy of bottom-composition-derived depth profiles, and the sensitivity of the model to depth profiles that are old, that have a slope error, or that are old and have a slope error.

## 4.0 RESULTS

### 4.1 MSI Verification

The results of the Best Data runs and Bottom-Composition-Based Depth Profile runs are shown in Table 3. This table also includes actual MSI calculated, in part, from ground truth measurements

Table 3 — MSI Verification. MSI Each Day Using Four Different Depth Profiles. *Foreshore*, *Bar*, and *Offshore* Depth Profiles are From Program SEDIMENT. Wind, Tide, and Wave Spectra for Each Day were Acquired Concurrently. Validation is Made with Available DELILAH Surf Zone Measurements. Bottom Row is the RMS of the Fractional Error for Each Profile Type for All Days Compared to MSI Validation in Right Column.

| DAY | MODEL AND $d_{foreshore}$ | MODEL AND $d_{bar}$ | MODEL AND $d_{offshore}$ | MODEL AND MINIGRID PROFILES | VALID MSI |
|---|---|---|---|---|---|
| 6 | 6.9 | 3.3 | 2.3 | 4.4 | 5.4 |
| 7 | 8.2 | 4.9 | 3.5 | 5.7 | 5.0 |
| 8 | 7.3 | 3.7 | 3.1 | 6.7 | 9.4 |
| 9 | 9.7 | 4.5 | 3.5 | 6.3 | 9.7 |
| 10 | 10.4 | 5.5 | 10.5 | 9.5 | 9.5 |
| 11 | 11.5 | 6.1 | 15.9 | 11.3 | 12.7 |
| 12 | 8.6 | 3.3 | 10.6 | 6.6 | 8.7 |
| RMS OF FRACTIONAL ERROR | 0.282 | 0.484 | 0.447 | 0.217 | 0 |

of the two most influential factors in the MSI formula: the highest significant wave height in the surf zone and the highest longshore current in the surf zone. Actual MSI is calculated by replacing the respective model-derived $h_{sig}$– and $v$-contributions to MSI with the respective contributions from the measurement values. The contributions from breaker angle, period, and type in the model output are not replaced, which biases the results of MSI validation in favor of the model.

The column *Valid MSI* contains the actual MSI, i.e., the best estimate of MSI for the time using the best ground truth information available. The simple fractional error in MSI for each of the separate bathymetric profiles ($M(d_i)$) with respect to the valid MSI ($M(d_{val})$) is defined as

$$\varepsilon_i = \frac{M(d_i) - M(d_{val})}{M(d_{val})} \quad . \tag{3}$$

The RMS ($E_i$) of the fractional error ($\in_i$) of $M(d_i)$ with respect to $M(d_{val})$ for all cases ($N$) is

$$E_i = \sqrt{\frac{\sum_i \in_i^2}{N}} \quad . \tag{4}$$

The RMS of the fraction of model-derived MSI to the actual MSI for each depth profile type is shown in the bottom row of Table 3. It is important to note:

(1) The mean error in MSI from the model using Best Data is about 22%.

(2) Each bottom-composition-based profile yielded less accurate results than the in situ profiles.

The comparison of model versus measured longshore current $v$, significant wave height $h_{sig}$, and surf zone width $SZ$ for each of the seven cases is given in Table 4. Tables 3 and 4 suggest that

Table 4 — Comparison of Model Estimates to Model-Measurement Estimates

| DAY HOUR (EST) | 6 OCT 1600 | 7 OCT 0700 | 8 OCT 1600 | 9 OCT 1300 | 10 OCT 1300 | 11 OCT 1000 | 12 OCT 1000 |
|---|---|---|---|---|---|---|---|
| *SZ*-MODEL (ft) | 204 | 71 | 241 | 262 | 268 | 377 | 348 |
| *SZ*-MODEL FORESHORE (ft) | 52 | 45 | 85 | 91 | 90 | 136 | 99 |
| *SZ*-VIDEO (ft) | 195 | 180 (est.) | 260 | 285 | 300 (est.) | 300 (est.) | 340 |
| $h_{sig}$-MODEL (ft) | 2.0 | 2.0 | 2.7 | 3.2 | 3.4 | 4.6 | 3.8 |
| $h_{sig}$-MODEL FORESHORE (ft) | 2.1 | 2.5 | 2.7 | 3.4 | 3.7 | 4.7 | 3.8 |
| $h_{sig}$-MEASURE (ft) | 1.8 | 2.3 | 2.7 | 3.6 | 4.0 | 3.3 | 4.1 |
| $v$-MODEL (kt) | 0.6 | 0.9 | 0.7 | 0.9 | 1.9 | 1.5 | 0.9 |
| $v$-MODEL FORESHORE (kt) | 1.2 | 1.2 | 1.1 | 1.6 | 1.7 | 1.9 | 1.3 |
| $v$-MEASURE (kt) | 1.0 | 0.6 | 1.6 | 1.9 | 1.7 | 2.4 | 1.5 |

the model contains intrinsic deficiencies that cause inaccurate estimates of longshore current and, to a lesser degree, significant wave height. The greatest deficiency in the model is in the representation of longshore current. Research in the ocean engineering community has not yet solved the problem of longshore current over a barred beach. Recent reports, specifically on DELILAH, demonstrate some small improvements, but no breakthroughs, in modeling longshore currents (Church and Thornton 1993; Lippmann et al. 1995; Lippmann et al. 1996; Reniers et al. 1995; Smith et al. 1993; Van Rijn and Wijnberg 1996). Until research breakthroughs occur, the Navy-Standard Surf Model MSI will be limited by longshore current modeling accuracy.

Also note that surf zone widths are all too narrow for model runs using the foreshore sediment type profile. What appears to be accurate model longshore current velocity estimates are due to the model improperly dissipating wave energy in the surf zone. The energy within the waves is actually released suddenly in the last few increments of the model integration, only yielding high currents next to shore. Such current profiles are physically unrealistic within a surf zone, although the peak values obtained next to shore agree quite well with actual measurement velocities that exist within a much wider surf zone. Although these model inaccuracies generate decent MSI estimates on 9–12 Oct, the foreshore sediment profile significantly overestimates MSI on 6 and 7 Oct. Such results could potentially and incorrectly preclude affirmative assault decisions for some landing craft.

### 4.2 MSI Errors Due to Slope Error and Profile Age

Figure 6 is a plot of the MSI values from the Best Data Runs and the Old Depth Profile Runs. The right endpoint of each curve is the MSI from the Best Data Run; the other points in each curve represent MSI values from old profiles. The highest valid MSI, 12.7, occurred on 11 Oct when the longshore current was a maximum of 2.4 kt. The relatively close agreement between the model-derived MSI and the valid MSI on this day is a result of combined errors in the model. Table 4 shows that the model essentially cancels the longshore current underestimation with an overestimation of significant wave height, resulting in an MSI comparable to the valid MSI.

The curves in Fig. 6 reveal the striking changes that can occur using out-of-date bathymetry profiles. Figure 6 demonstrates that using the 8 Oct bathymetry with wave, wind, and tide inputs from other days results in a wide range of MSI inaccuracies. It is likely that the 8 Oct depth profile caused higher MSI than validated on 10, 11, and 12 Oct due to the steeper bathymetric gradient near the edge of the water on that profile relative to the other depth profiles. There is also an absence of any offshore bar on the 8 Oct profile (Fig. 3).

The simple fractional error in MSI for changing profile slope ($\Delta\gamma$) and age ($\Delta t$) $M(d_{t-\Delta t,\gamma+\Delta\gamma})$ with respect to $M(d_{t,\gamma})$ is defined as

$$\varepsilon_{t-\Delta t,\gamma+\Delta\gamma} = \frac{M(d_{t-\Delta t,\gamma+\Delta\gamma}) - M(d_{t,\gamma})}{M(d_{t,\gamma})} . \tag{5}$$

The fractional error results of the Best Data runs, Old Depth Profile runs, and Depth Profile Error runs are given in Figs. 7–11 and Table 5. These data demonstrate a general tendency for slope errors that are too steep to yield MSI values higher than validation. Shallow slope errors yield MSI values that are too low. Some depth profiles, i.e., the 8 and 11 Oct profiles and those derived from them, yield more anomalous results than others. Fractional errors of up to 260% occur on 8 Oct for

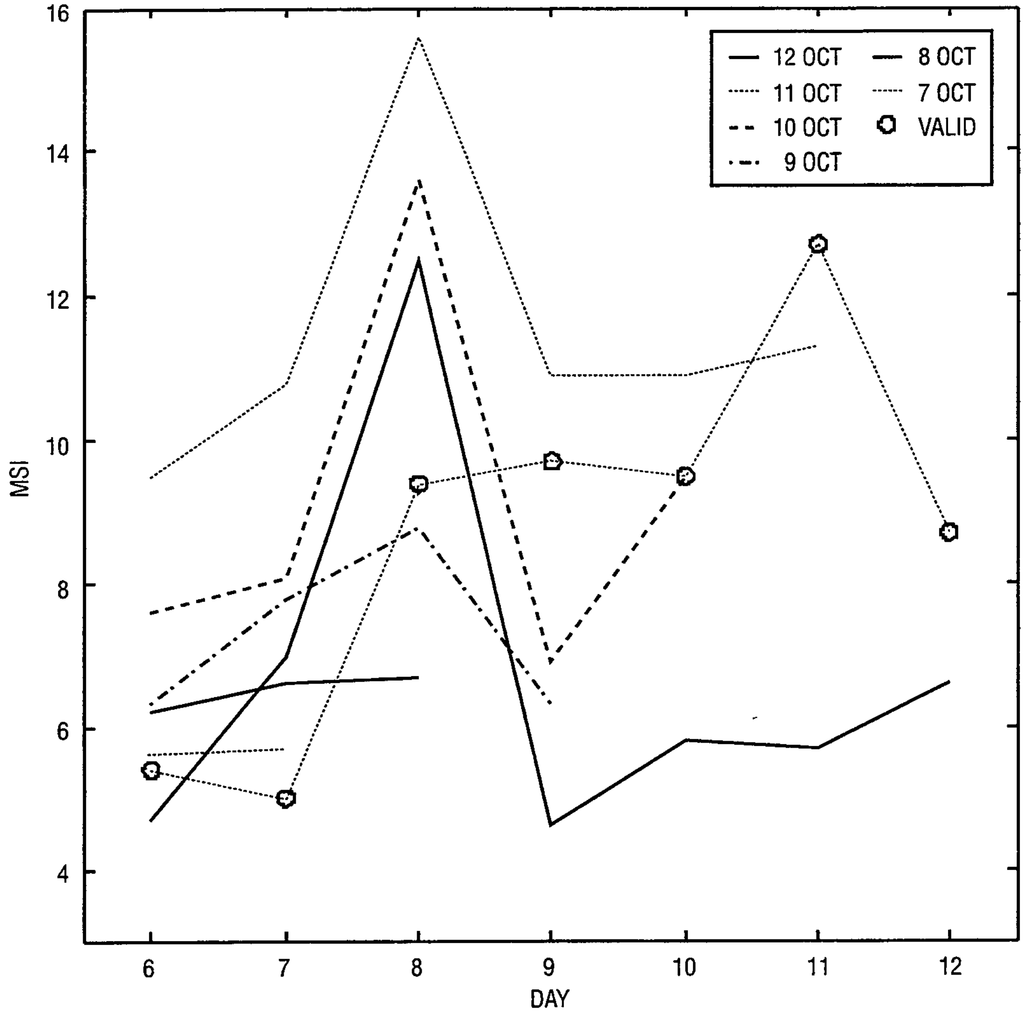


Fig. 6 — Modified surf index from Measurements, Best Data Runs, and Old Depth Profile runs

a 25% slope error. MSI fractional errors of 20–30% occur on almost every day for slope errors greater than 10%. These results demonstrate that a timely depth profile with slope accuracy within 10% error is very important to surf estimation accuracy. MSI errors due to slope error, profile age, and combined slope and age error are discussed in detail in the following subsections.

### *4.2.1 Slope Error*

The sensitivity of model MSI to profile slope error, all else being held constant, is estimated by the following method. For profiles of time $t$, a pair of depth profiles that are different by a slope $\Delta\gamma$ will yield MSI values $M(d_{t,\gamma})$ and $M(d_{t,\gamma+\Delta\gamma})$. The simple fractional error in $M(d_{t,\gamma+\Delta\gamma})$ with respect to $M(d_{t,\gamma})$ is defined as

$$\in_{t,\gamma+\Delta\gamma} = \frac{M(d_{t,\gamma+\Delta\gamma}) - M(d_{t,\gamma})}{M(d_{t,\gamma})} . \tag{6}$$

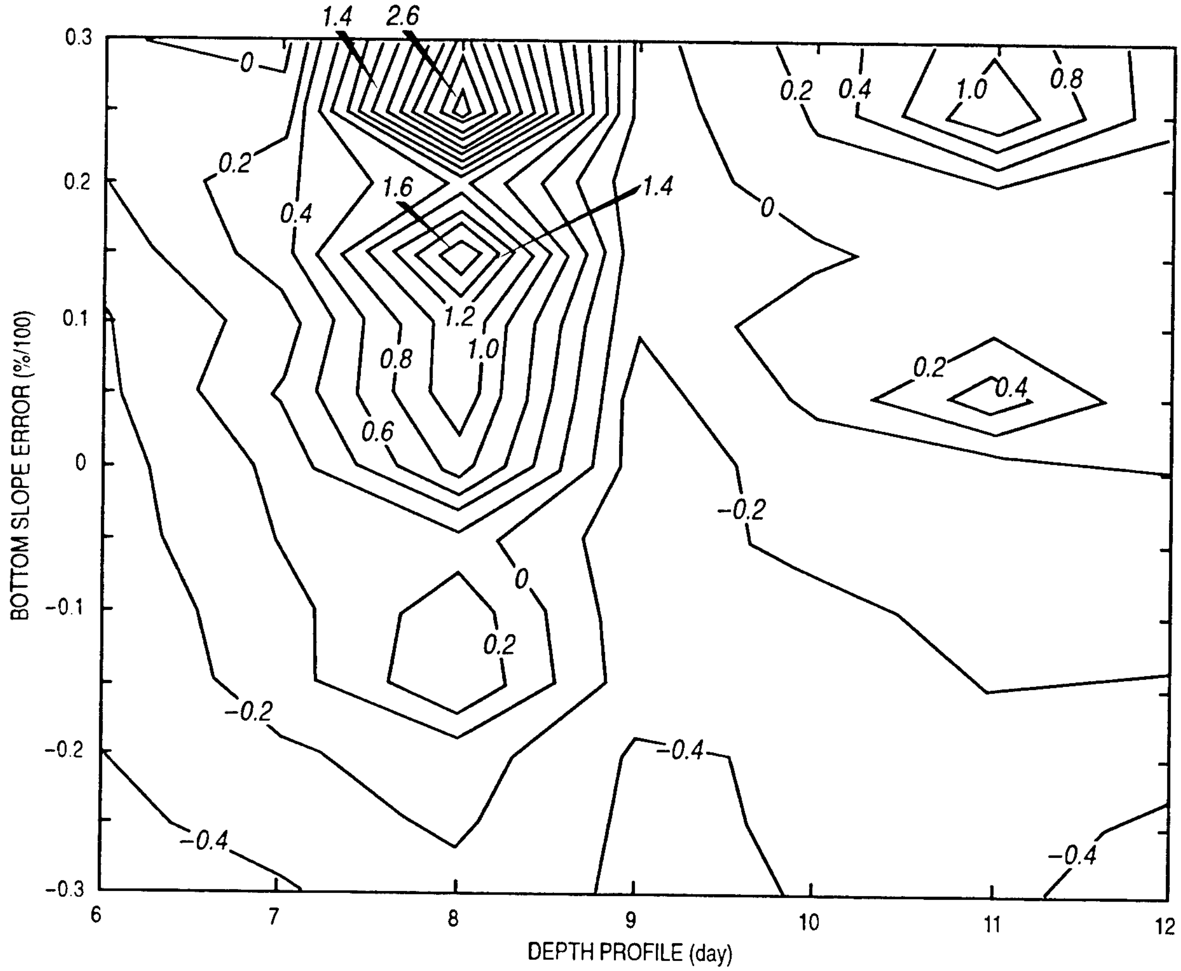


Fig. 7 — Contours of MSI fractional error for Depth Profile Error runs for 12 Oct using 12 Oct DELILAH data inputs and profiles $d_{t,\gamma}$

The RMS of the fractional error of all $[M(d_{t,\gamma})\ ,\ M(d_{t,\gamma+\Delta\gamma})]$ pairs with respect to $M(d_{t,\gamma})$ is

$$E_{\Delta\gamma} = \sqrt{\frac{\sum_t \sum_\gamma \in^2_{t,\gamma+\Delta\gamma}}{N}}\ , \tag{7}$$

where $t$ covers all days, 6–12 Oct. Slope error is found for all $\Delta\gamma$ such that

$$\Delta\gamma = [-0.6, -0.55, -0.5, ..., -0.05; 0.05, 0.10, 1, 5, \ ..., 0.6]\ . \tag{8}$$

$N = 7\ \mathrm{d} \times |0.6\ /\Delta\gamma|$. For $\Delta\gamma = \pm 0.05$, $N = 84$. $E_{\Delta\gamma}$ provides a measure of the sensitivity of the model to slope error for which model skill is not considered.

The resulting $E_{\Delta\gamma}$ values are given in Fig. 12. This figure reveals that positive slope errors, representing depth profiles that are too steep, increase linearly due to a progressive narrowing of

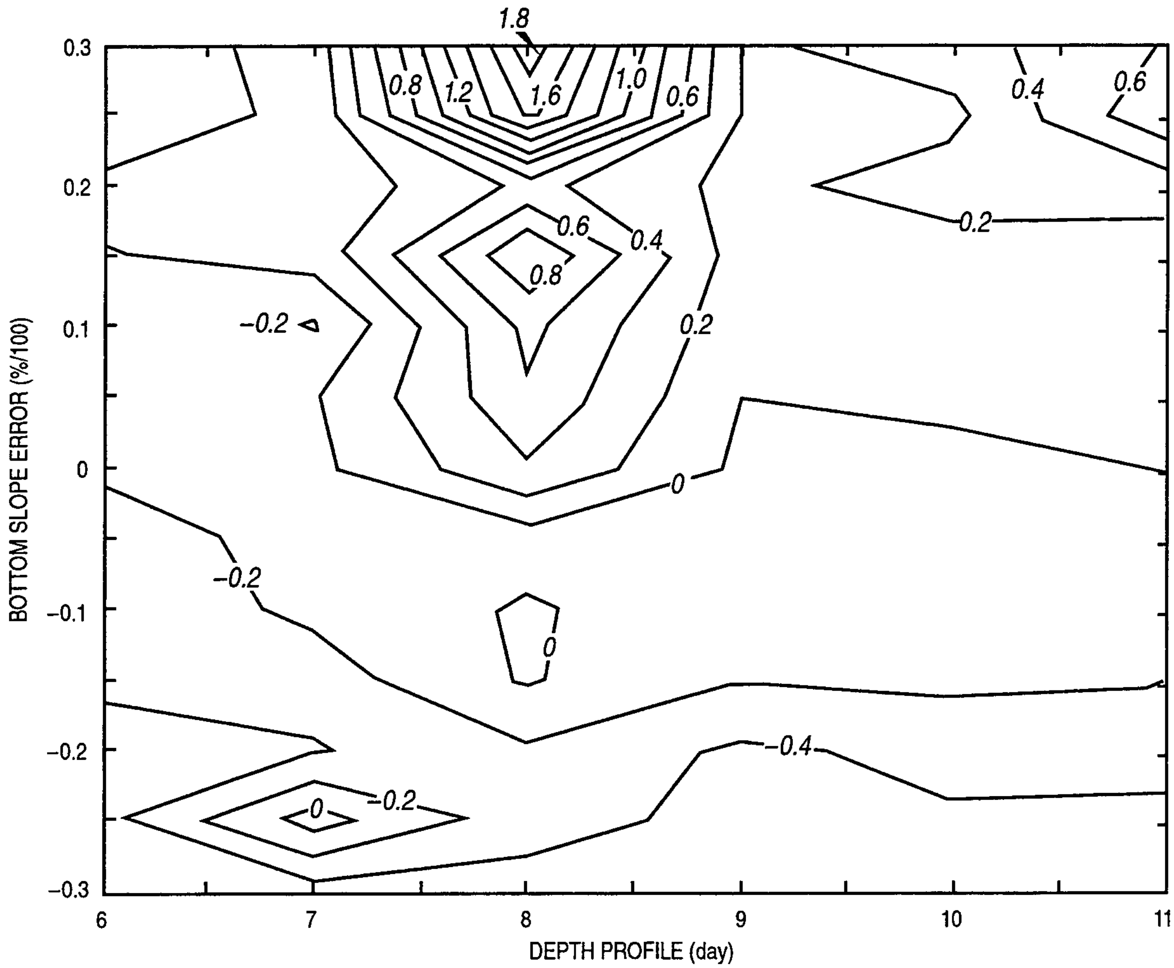


Fig. 8 — Contours of MSI fractional error for Depth Profile Error runs for 11 Oct using 11 Oct DELILAH data inputs and profiles $d_{t,\gamma}$

the surf zone. Thus, a steeper slope generates higher MSI values. A depth profile estimate containing a slope error 10% too steep relative to ground truth will generate MSI estimates approximately 19% too high. Similarly, slope errors 20% too steep generate MSI estimates about 23% too high; 30% slope errors generate MSI about 30% too high.

Negative slope errors, representing depth profiles that are too shallow, have a more complicated structure owing to the influence of the bar that is present on most of the baseline profiles. The presence of the bar causes various differences in surf zone width, breaker type, longshore current, and subsequently, MSI estimates between model runs. A depth profile that underestimates the true slope by 10% will generate MSI estimate errors approximately 13% too low. Similarly, slope underestimates of 20% and 30% will generate MSI errors about 10% and 15% too low, respectively.

It should be noted that RMS errors of 20% or less are confined to slope errors from –0.3 to 0.1. RMS errors less than 10% are confined only to slope errors of –0.2, –0.15, and –0.05. The asymmetry of the error about zero indicates that the sign of slope error is an important factor in estimating MSI error. Overestimating the true bathymetric slope by even 5% generates MSI estimates more than 10% higher than actual. However, underestimating bathymetric slope by less than 20%

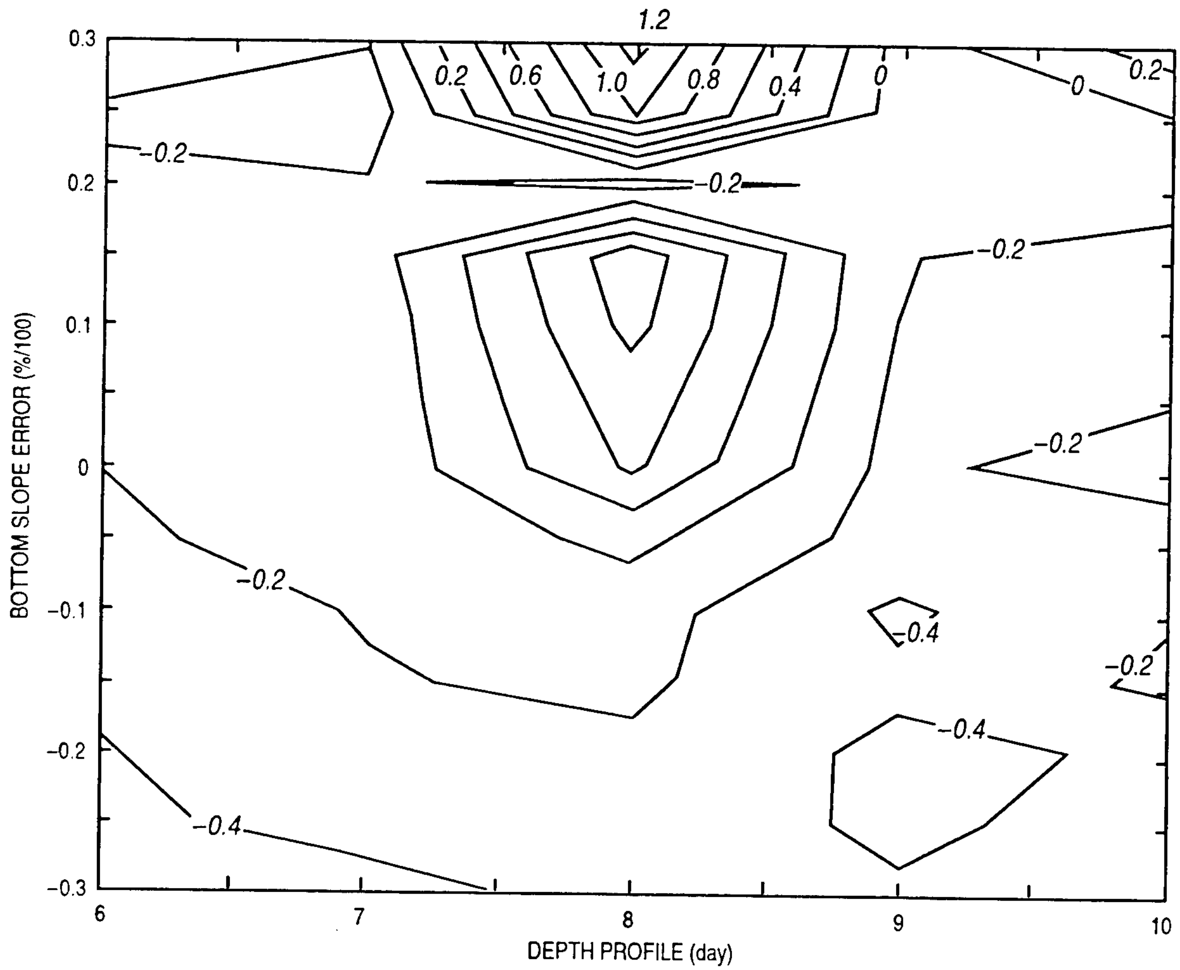


Fig. 9 — Contours of MSI fractional error for Depth Profile Error runs for 10 Oct using 10 Oct DELILAH data inputs and profiles $d_{t,\gamma}$

can generate MSI estimates that are 10% or less lower than actual. Thus, techniques used to estimate slope should be careful not to overestimate the actual slope at all, but also not underestimate the slope by more than 20%.

### *4.2.2 Age of Depth Profile*

The sensitivity of model MSI to the age of depth profiles, all else being held constant, is estimated by the following method. A pair of depth profiles that are $\Delta t$ days apart and having the same slope error $\gamma$ will yield MSI values $M(d_{t,\gamma})$ and $M(d_{t-\Delta t,\gamma})$. The simple fractional error is defined as

$$\epsilon_{t-\Delta t,\gamma} = \frac{M(d_{t-\Delta t,\gamma}) - M(d_{t,\gamma})}{M(d_{t,\gamma})} . \tag{9}$$

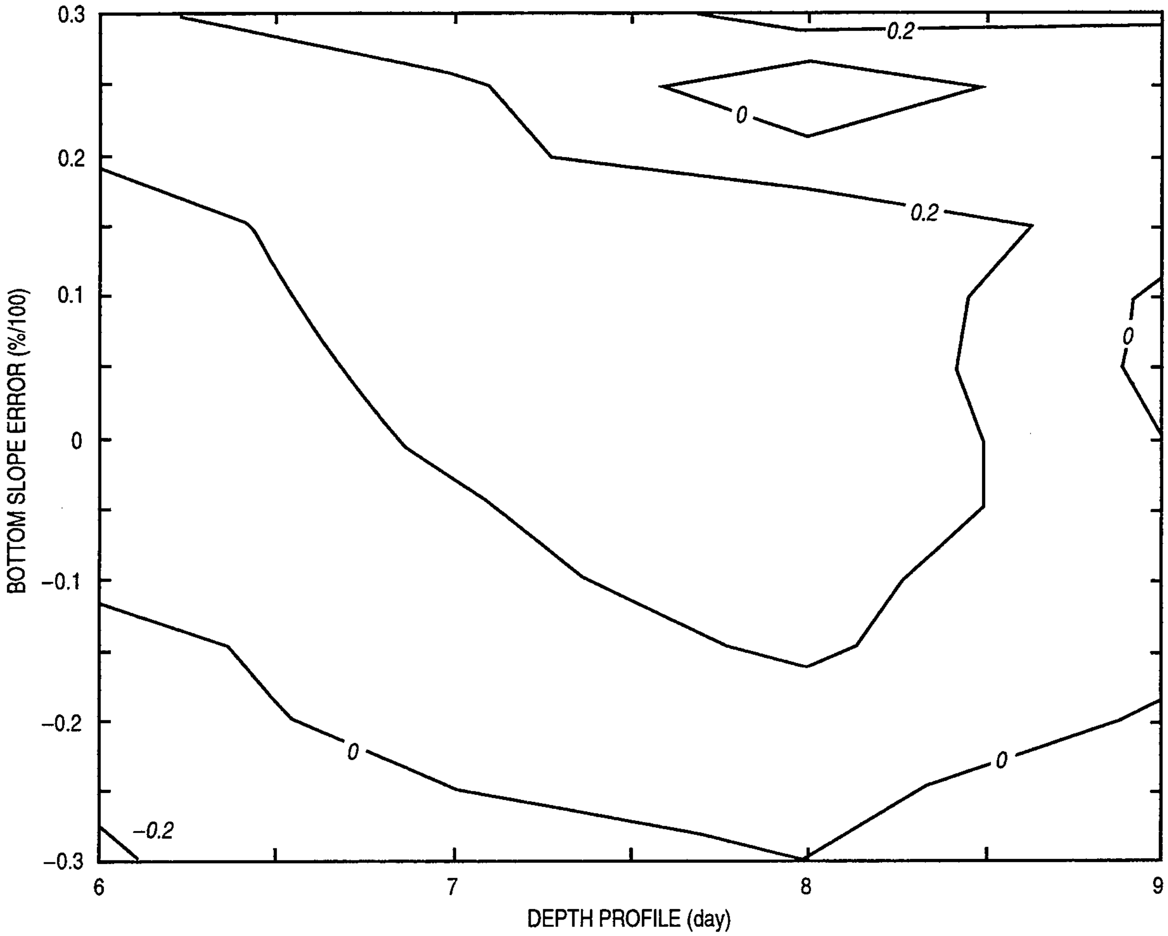


Fig. 10 — Contours of MSI fractional error for Depth Profile Error runs for 9 Oct using 9 Oct DELILAH data inputs and profiles $d_{t,\gamma}$

| $\gamma$ | 6 OCT | 7 OCT |
|---|---|---|
| 0.03 | 0.16 | 0.21 |
| 0.25 | 0.14 | 0.18 |
| 0.20 | 0.11 | 0.14 |
| 0.15 | 0.09 | 0.09 |
| 0.10 | 0.05 | 0.07 |
| 0.05 | 0.02 | 0.02 |
| 0 | −0.02 | 0 |
| −0.05 | −0.04 | −0.04 |
| −0.10 | −0.11 | −0.07 |
| −0.15 | −0.14 | −0.14 |
| −0.20 | −0.18 | −0.18 |
| −0.25 | −0.19 | −0.21 |
| −0.30 | −0.25 | −0.25 |

Table 5 — MSI Fractional Error Relative to Valid MSI from Depth Profile Error Runs for 7 Oct Using 7 Oct DELILAH Data Inputs and Profiles $d_{t,\gamma}$

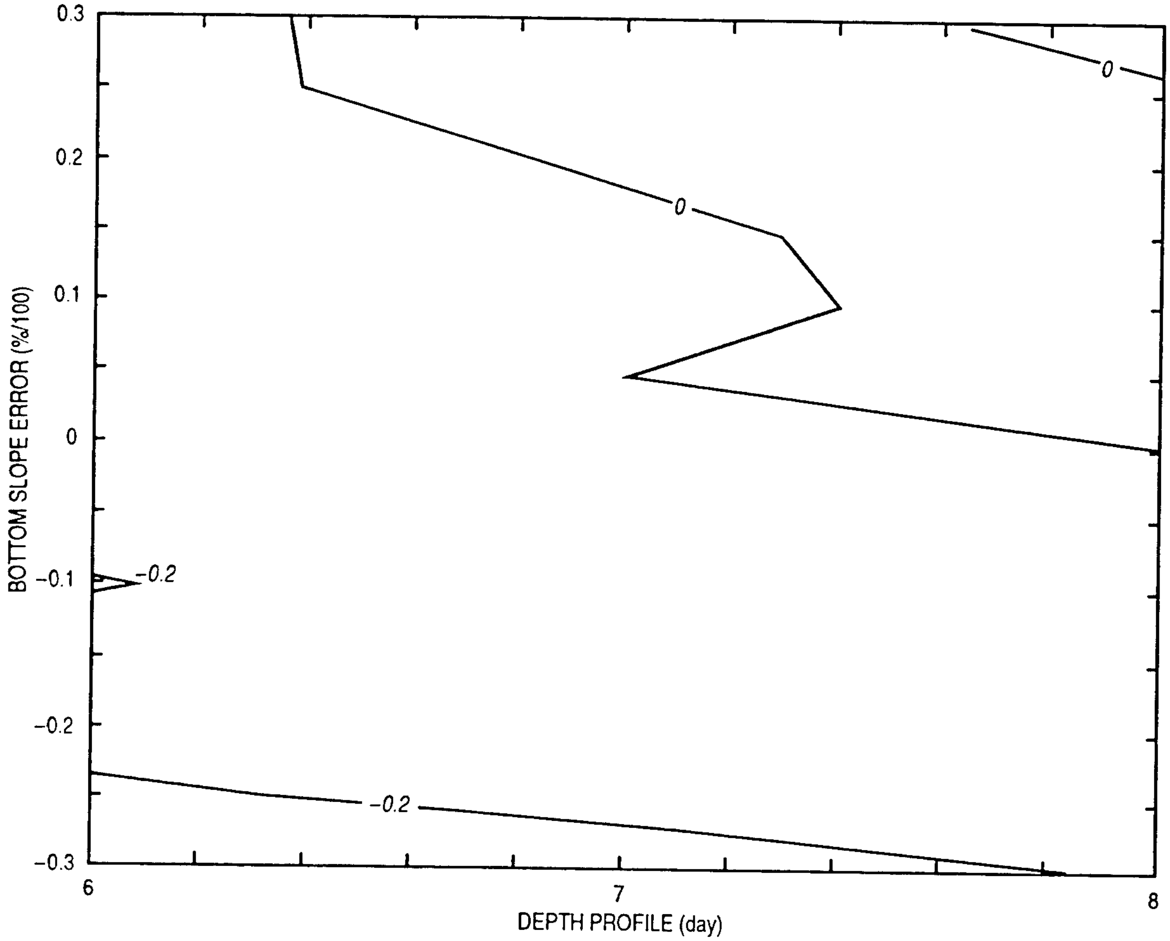


Fig. 11 — Contours of MSI fractional error for Depth Profile Error runs for 8 Oct using 8 Oct DELILAH data inputs and profiles $d_{t,\gamma}$

The RMS of the fractional error of all MSI pairs $\Delta t$ days apart with respect to $M(d_{t,\gamma})$ is

$$E_{\Delta t} = \sqrt{\frac{\sum_{t}\sum_{\gamma} \in^2_{t-\Delta t,\gamma}}{N}} \quad . \tag{10}$$

such that $\gamma$ is [−0.30, −0.25, −0.20 ... 0.30], $\Delta t$ = [1 to $t-6$] for $t$ = [7, 8, 9, 10 11, 12 (Oct)], and $N = 7 - \Delta t$ d × 13 slope errors. For $t$ = 12 (Oct) and $\Delta t$ = 1 d, $N$ = 78. $E_{\Delta t}$ provides a measure of the sensitivity of the model to profile age for which model skill is not considered. The resulting values of $E_{\Delta t}$ are displayed in Table 6.

The results show that out-of-date profiles generate RMS errors between 19 and 44%. Profiles 1 d old caused RMS errors of 42%. The large MSI errors are primarily due to the 8 Oct profile that contained the sharpest gradient nearshore and had no offshore bar. The anomalously high MSI values from the 8 Oct profile are shown in Figs. 7–9. The 8 Oct MSI values are included in all $E_{\Delta t}$ for $\Delta t \leq 4$ d, which may account for the relatively high errors for $\Delta t$ = [1, 2, 3, 4]. These results demonstrate that profile age can be an important factor in MSI accuracy. Figure 3 reveals that the

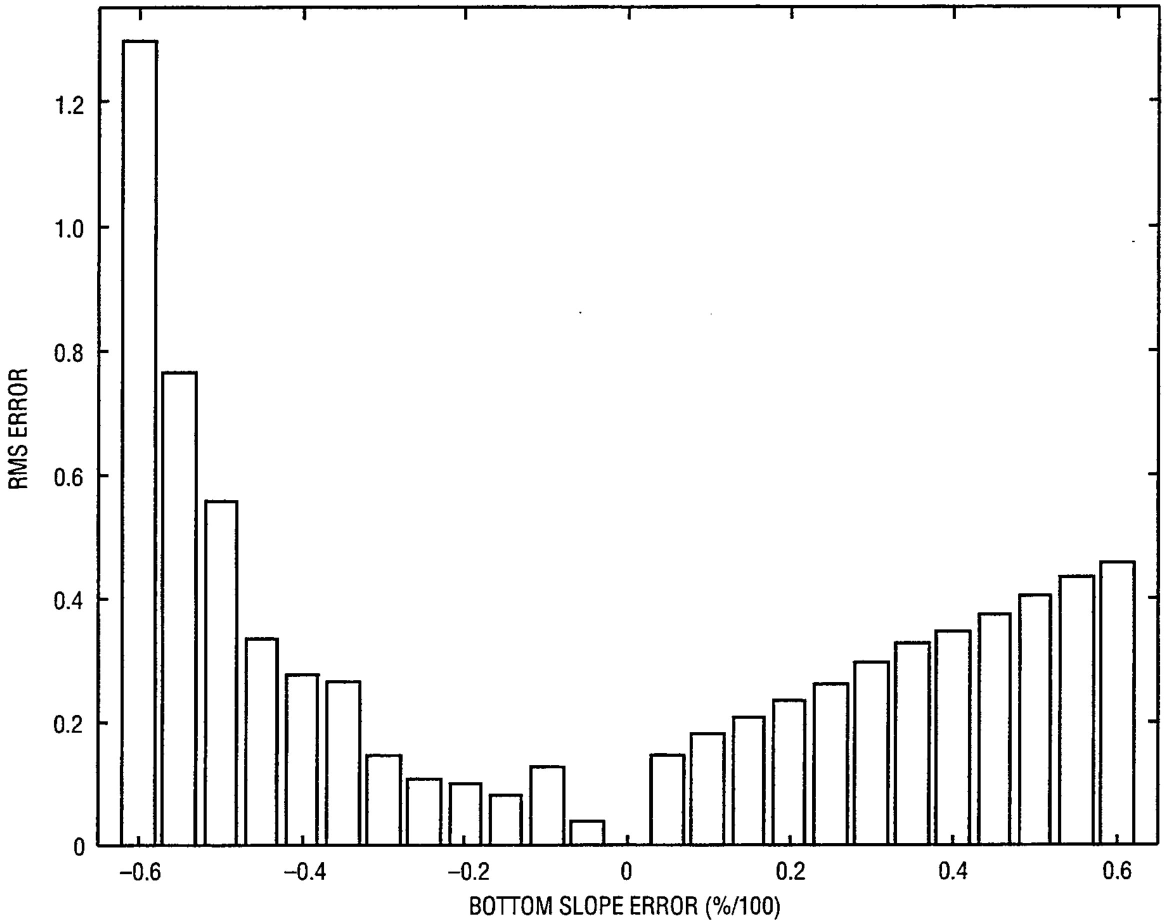


Fig. 12 — RMS fractional error of MSI due to depth profile slope error

| $\Delta t$ (d) | $E_{\Delta t}$ |
|---|---|
| 1 | 0.42 |
| 2 | 0.44 |
| 3 | 0.30 |
| 4 | 0.43 |
| 5 | 0.25 |
| 6 | 0.19 |

Table 6 — MSI Sensitivity to Age of Depth Profile

bathymetry was significantly changing during this week of data. Utilizing an out-of-date bathymetry profile for any of these days results in significant MSI estimation error from the model.

### *4.2.3 Total Bathymetry Error*

The sensitivity of model MSI to bathymetry errors due to both slope errors and age ($E_b$) is estimated by the following method

$$E_b = \sqrt{E^2_{\Delta\gamma} + E^2_{\Delta t}} \ . \tag{11}$$

A contour plot of $E_b$ for $\Delta\gamma$ = [−0.15, −0.10, ..., 0.15] and $\Delta t$ = [0, 1, ..., 6] is shown in Fig. 13. For this study, it is evident that MSI errors less than 10% can only be obtained if $\Delta t$ is less than 1 d and $\Delta\gamma$ is between −0.08 and +0.03. MSI errors less than 20% are confined to $\Delta t$ less than 1 d and $\Delta\gamma$ between −0.3 and +0.14. These results demonstrate that a timely and accurate depth profile within 10% slope error is very important for estimating MSI within 10% of actual conditions.

### *4.2.4. Combined Error*

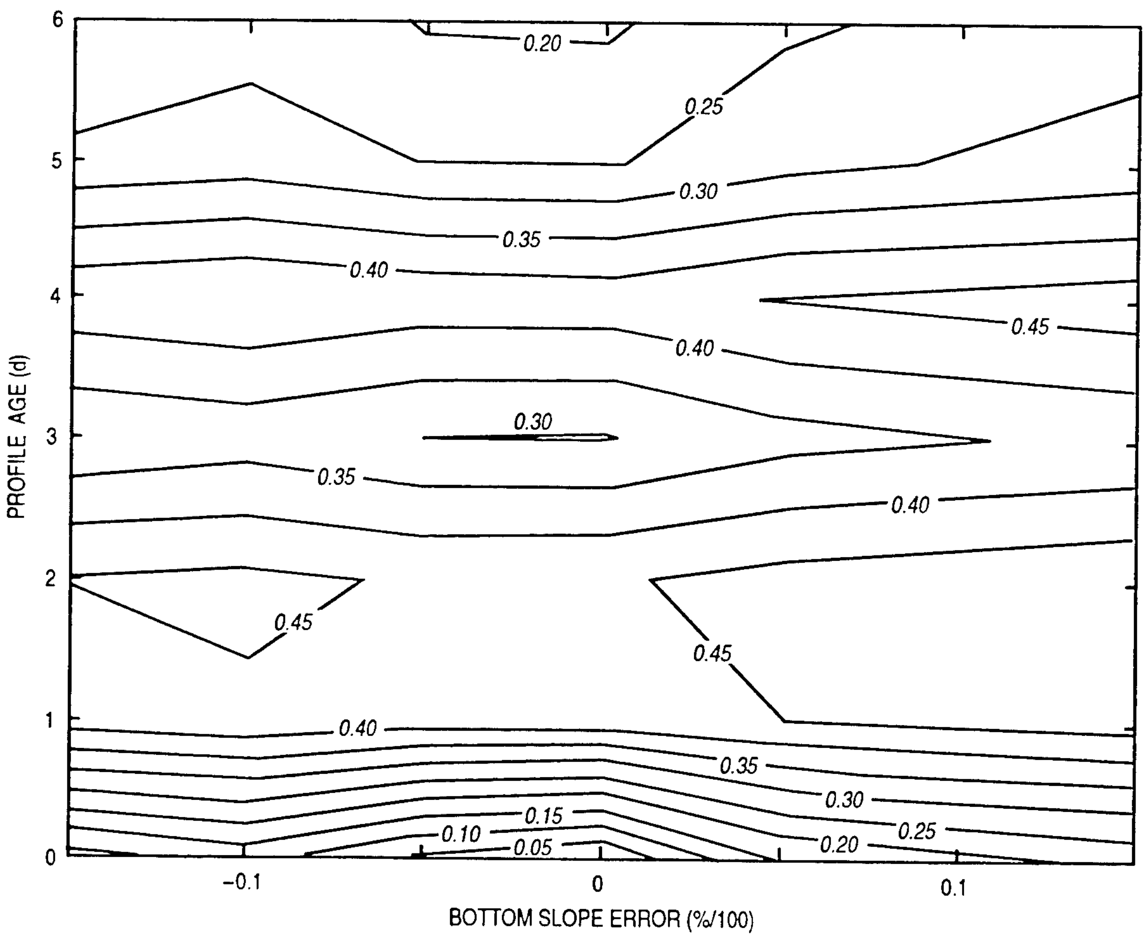


Fig. 13 — MSI error due to depth profile error for $\Delta\gamma$ = [−0.15, −0.1, −0.05, ..., 0.15] and profile age for $\Delta t$ = [0, 1, 2, ..., 7]

The total MSI error $E_{total}$ due to model inaccuracy $E_{model}$, $E_{\Delta\gamma}$, and $E_{\Delta t}$ is given as

$$E_{total} = \sqrt{E^2_{model} + E^2_{\Delta\gamma} + E^2_{\Delta t}}\ , \tag{12}$$

where $E_{model}$ is 0.22. A contour plot of $E_{total}$ for $\Delta t = [0, 1, 2, ..., 6]$ and $\Delta\gamma = [-0.15, -0.10, -0.05, ..., 0.15]$ is shown in Fig. 14 where the maximum is greater than 0.50 at $t$ = 1–2 d and $\Delta\gamma > 0.05$ and also for $t$ = 4 d and $\Delta\gamma$ greater than 0.10. These extremely high combined errors again reveal the great importance of obtaining accurate, timely depth profiles for operational MSI estimates.

It is noted that $E_{total}$ should include the influence of errors in wind speed, wind direction, and offshore waves. The standard version of the surf model does not use in situ directional wave spectra, but the wave parameters for sea and swell: height, period, and direction. This study bypasses any inherent imperfection in the model's treatment of wave spectra by using precisely measured in situ spectra properly refracted and shoaled. Errors in input wave parameters may, of course, add more error into model-derived MSI estimates.

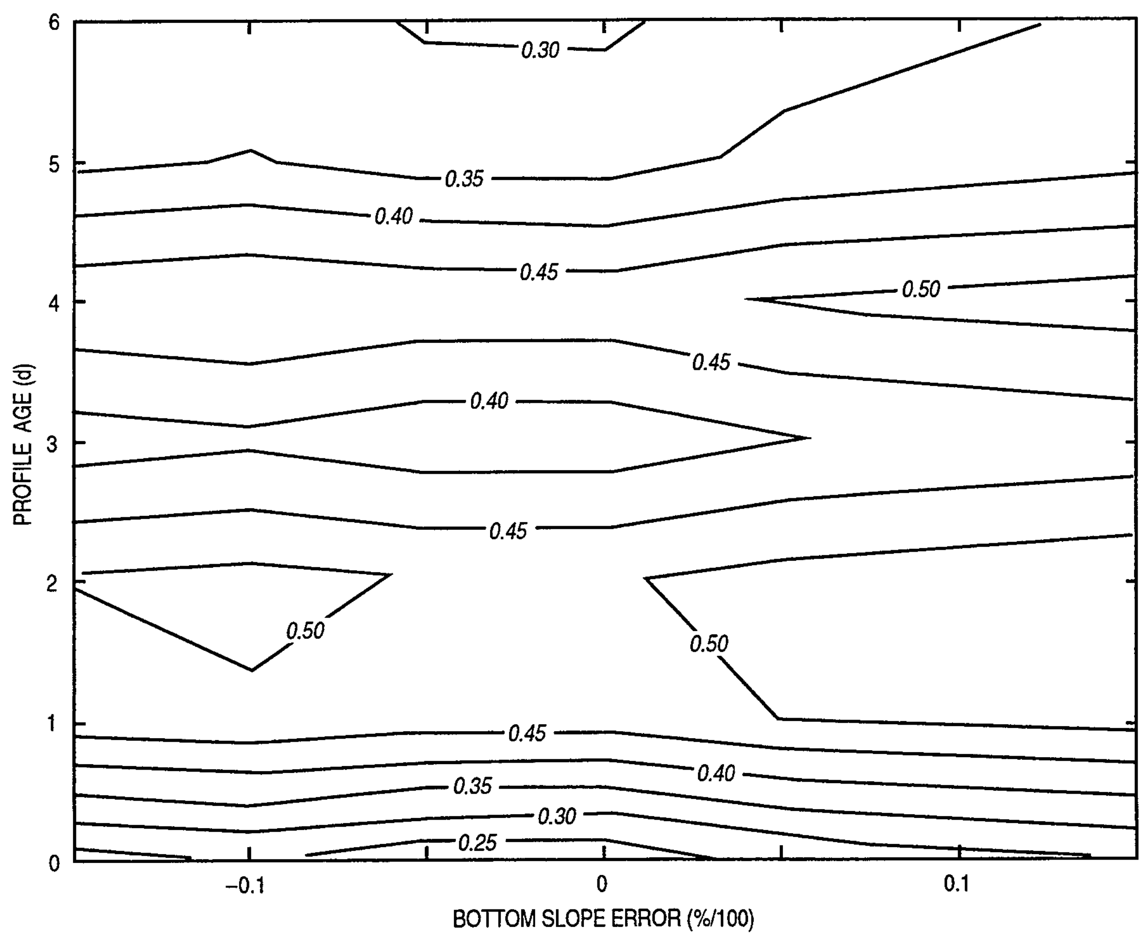


Fig. 14 — Total MSI error to due to model error, depth profile error for $\Delta\gamma = [-0.15, -0.10, -0.05, ..., 0.15]$ and profile age for $\Delta t = [0, 1, 2, ..., 7]$

## 5.0 SUMMARY AND CONCLUSIONS

The error in MSI using the surf model can be categorized into several parts, but only two are considered in this study. The first is error due to actual model inaccuracies that have been quantified using in situ surf zone measurements and other measurements obtained from the DELILAH data set. The second is from depth profile errors introduced by either the age of the profile or a simulated slope error. These errors have been estimated using actual depth profiles derived from daily DELILAH surveys and erroneous, synthetic profiles derived from these original surveys.

The error within the model can be subcategorized into model estimation errors of significant wave height, surf zone width, and longshore current. These errors are interrelated, so the relative significance of each is not precisely quantified, though model accuracy for 7 consecutive days has been shown. The overall accuracy of MSI using the surf model and the best ground truth (Best Data) available is found to be approximately 22%. The most significant partial inaccuracy in the model is in longshore current, which contributes a factor of 3 for every knot of longshore current speed. Work is in progress to improve model surf zone width estimates, which should also improve significant wave height estimates. Longshore current model estimation errors remain an unresolved research problem. Although present research continues to focus on this issue, only small improvements have been attained to date. Surf zone research emphasis should continue on longshore current modeling.

Table 7 shows a graphical depiction of MSI limits for 10 amphibious vehicles and craft as described in the *Joint Surf Manual*. The table also depicts MSI estimates obtained from the Best Data, coarse sand bottom-composition profile ($d_{foreshore}$), and validated MSI estimates for this study. These values have been rounded to the nearest integer value. The table shows that model-derived MSI from the Best Data may sometimes, as in the 9 Oct case, be unacceptable for operational purposes. In this instance, the model significantly underestimates surf conditions even though the latest in situ bathymetry was used.

The foreshore sediment profile overestimates MSI on 6 and 7 Oct. These value results could potentially and incorrectly preclude an assault decision for some landing craft types. The foreshore sediment profile underestimates MSI on 8 Oct, but provides reasonable results on the remaining days analyzed. However, these apparently correct values are obtained due to model inaccuracies as demonstrated in Table 4 and Sec. 4.1. Essentially, model utilization of the foreshore sediment profile results in surf zone widths that are unrealistically too narrow and that force all of the dissipating wave energy to release suddenly nearshore, yielding anomalously high longshore currents and MSI values. These model inaccuracies actually help the model generate apparently good MSI at times. However, the foreshore sediment profile results are significantly higher and more severe than valid conditions on 6 and 7 Oct, demonstrating that the profile leads to inconsistent and inaccurate results.

Old and outdated profiles also add inaccuracy to MSI. The RMS error for 1-day-old profiles is 0.42 for the data analyzed in this study. The combined error due to inaccuracy in the model and age of the depth profile yields a single day uncertainty as follows

$$One\ Day\ MSI\ Err = \sqrt{\left(.22^2 + .42^2\right)} \times 100 = \pm 47\% \,. \tag{13}$$

For an MSI of 7, model-derived MSI could conceivably range from 3.7 to 10.3, though errors of this magnitude are not found in the results from the Old Depth Profile runs. From the Old Depth

Table 7 — MSI Limits for Navy Vehicles/Craft, MSI from $d_{foreshore}$ Runs (Foreshore), Best Data Runs (BEST), and Validated MSI (VALID)

| | |
|---|---|
| LCVP | 5 |
| LARC | 6 |
| CAUSEWAY | 6 |
| SELF PROPELLED | 7 |
| BARGE (Pontoon) | 7 |
| LCM 6 | 8 |
| LCM 8 | 8 |
| LVTP-5 | 8 |
| LARC V | 9 |
| LCU | 12 |
| 6 Oct Foreshore | 7 |
| 6 Oct BEST | 4 |
| 6 Oct VALID | 5 |
| 7 Oct Foreshore | 8 |
| 7 Oct BEST | 6 |
| 7 Oct VALID | 5 |
| 8 Oct Foreshore | 7 |
| 8 Oct BEST | 7 |
| 8 Oct VALID | 9 |
| 9 Oct Foreshore | 10 |
| 9 Oct BEST | 6 |
| 9 Oct VALID | 10 |
| 10 Oct Foreshore | 10 |
| 10 Oct BEST | 10 |
| 10 Oct VALID | 10 |
| 11 Oct Foreshore | 12 |
| 11 Oct BEST | 11 |
| 11 Oct VALID | 13 |
| 12 Oct Foreshore | 9 |
| 12 Oct BEST | 7 |
| 12 Oct VALID | 9 |

LCVP – Landing Craft, Vehicle, Personnel

LARC – Light Amphibious Recovery Craft

LCM – Landing Craft, Mechanized

LVTP – Landing Vehicle, Tracked, Personnel

LARC V – Lighted Amphibious Resupply Cargo

LCU – Landing Craft, Utility

Profile runs, the highest 1 d fractional error was 40% using the 8 Oct depth profile to predict 9 Oct MSI (see Fig. 6).

Bathymetric slope estimation errors add more uncertainty to model-derived MSI. Slope errors that are too steep generate MSI values that are too high relative to ground truth measurements. Likewise, slope errors that are too shallow result in MSI estimates that are too low. However, the relationship is not linear and is complicated by the influence of the offshore bar. Techniques utilized to estimate slope of bathymetric profiles must not overestimate the slope at all and not underestimate it by more than 20% if MSI errors less than 10% are desired. However, combined with depth profile age, estimating MSI within 10% accuracy requires depth profile slope errors better than 10% and profiles less than 1 d old.

Improvements in MSI estimates can be made in two ways. The first calls for improvements in the surf model physics. As has been stated, the model does not reliably represent longshore current. Although work is underway, there is no foreseeable near-term solution to this difficult problem. Recent theories are limited to particular processes or are tied to empirical formulations derived for specific locations. Expanding the model from one dimension (cross-shore) to two dimensions (alongshore and cross-shore) or three dimensions (cross-shore, alongshore, and including vertical processes) would be costly and require much more input information than currently used by the model.

Since MSI is best derived from ground truth measurements, a practical approach to improving MSI and other descriptions of surf zone properties is to obtain in situ surf zone measurements from deployed instruments. Nichols and Earle (1996) have described a coupled wave, buoy-surf model system developed for the Tactical Oceanographic Warfare Office, in which the AN/WSQ-6 deployable directional wave buoy (Earle and Selsor 1994) was used to provide directional wave spectrum input to the surf model during the Combined Joint Task Force Exercise 96/Purple Star. The Clandestine Littoral Acoustic Module is an acoustic swimmer board system for automated data collection and rapid hydrographic mapping that provides nearshore depth profile information (Navarro et al. 1994). In view of its importance, some method of directly measuring longshore current in the surf zone should also be investigated. Development of such a system for amphibious warfare applications would be a very challenging endeavor because of the natural severity and military hazards inherent to the surf zone. However, if successful, the system would provide better surf zone current descriptions than are now possible from the surf model alone. Utilization of such systems in denied areas may not always be feasible, so remotely sensed methods to obtain directional wave spectra, nearshore depth profiles, and longshore currents should be actively pursued as well.

A larger question concerns the application of MSI as an overall guide to surf conditions. MSI may actually be too general of a number to be an accurate operational force guide. The *Joint Surf Manual* limits the LVTP-7 (Landing Vehicle, Tracked, Personnel) by wave period and type of surf and limits the LCAC by wave height and payload rather than MSI. Operational limitations of the Amphibious Assault Vehicles—AAVC-7A1 (Assault Amphibian Vehicle, Control), AAVP-7A (Assault Amphibian Vehicle, Personnel), and AAVR-7 (Assault Amphibian Vehicle, Recovery)—are based on specific combinations of wave height, type of surf, and wave steepness. Criteria for the Advanced Amphibious Assault Vehicle are under development and will likely be based on specific surf properties. It may be necessary to reexamine the application of MSI to all amphibious vehicles and craft. A decision tree or truth table approach may be better than using a single number in which errors in competing factors are spuriously cancelled in the final result. Establishing specific surf zone criteria for specific craft would, by knowing the likely error in particular model input and output parameters, allow more precise estimation of the error in forecast and nowcast surf zone properties. The surf model presently calculates MSI from the maximum longshore current and

significant wave height in the surf zone, though these maxima may not occur at the same cross-shore location. As the model is improved, the maximum local MSI throughout the surf zone may offer a more realistic representation of surf conditions.

This study has used the DELILAH data set, which is an extensive collection of precise ground truth measurements for a specific barred beach. The results should not be used to characterize model-derived MSI accuracy for all beaches, especially planar beaches where the surf model has been shown to provide more accurate estimates of longshore current (Earle 1989) than shown in this study. In addition, this study has focused on only 1 wk of data obtained at one location. Future analyses could include several weeks of data for longer comparison results. Nevertheless, the results of this study strongly suggest that model-derived MSI estimates for barred beaches should be used cautiously as a substitute for in situ surf zone observations. Recent interest in the littoral has generated increased awareness of the importance of the Navy surf model and work is underway to evaluate the current version, as in this report, and to correct its weaknesses. This report has demonstrated not only that model improvements are necessary, but that accurate inputs to the model are critical, specifically nearshore depth profile. It should again be noted that inaccuracies in wind, tide, and most importantly wave inputs, are not considered here. Errors in these parameters may also significantly affect surf forecast accuracy.

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